

Neutrino-nucleus interaction and supernova r -process nucleosynthesis

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We discuss various neutrino-nucleus interactions in connection with the supernova r -process nucleosynthesis, which possibly occurs in the neutrino-driven wind of a young neutron star. These interactions include ν_e and $\bar{\nu}_e$ absorptions on free nucleons, ν_e captures on neutron-rich nuclei, and neutral-current $\nu_{\mu(\tau)}$ and $\bar{\nu}_{\mu(\tau)}$ interactions with α -particles and neutron-rich nuclei. We describe how these interactions can affect the r -process nucleosynthesis and discuss the implications of their effects for the physical conditions leading to a successful supernova r -process. We conclude that a low electron fraction and/or a short dynamic time scale may be required to give the sufficient neutron-to-seed ratio for an r -process in the neutrino-driven wind. In the case of a short dynamic time scale, the wind has to be contained during the r -process. Possible mechanisms which can give a low electron fraction or contain the wind are discussed.

1. INTRODUCTION

In this paper we discuss the role of neutrino-nucleus interactions in a recent model of the supernova r -process nucleosynthesis. In this model, the r -process occurs in the neutrino-driven wind of a young neutron star [1]. The winds leave the neutron star at times $t \gtrsim 1$ s after its creation by the supernova explosion, and last for ~ 10 s, the Kelvin-Helmholtz cooling time scale of the neutron star. The attractive feature of this model is the simple characterization of its physical conditions by the neutron star properties and the supernova neutrino flux [2]. The physical conditions relevant for the r -process nucleosynthesis are the electron fraction, the entropy per baryon, the dynamic time scale, and the mass loss rate in the wind. These conditions are determined mostly by ν_e and $\bar{\nu}_e$ absorptions on the free nucleons in the wind. However, the presence of significant neutrino flux also introduces various other interaction processes between neutrinos and nuclei, which prove to be interesting and important for the possible r -process nucleosynthesis in this model. In Sec. 2, we describe some salient features of the r -process nucleosynthesis in the neutrino-driven wind. In Sec. 3, we focus on the role of ν_e and $\bar{\nu}_e$ absorptions on free nucleons in determining the electron fraction in the wind. In Sec. 4, we investigate the influence of the α -particles in the wind on setting the electron fraction and the neutron-to-seed ratio for the r -process. In particular, we describe how neutrino spallations on the α -particles can alter the path of the nuclear flow leading to the seed nuclei. We discuss the requirement on the conditions in the wind to avoid or counteract various effects concerning the α -particles.

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In Sec. 5, we examine the competition between ν_e captures on neutron-rich nuclei and nuclear β -decays during the r -process. We discuss the implications of this competition for the dynamic time scale and the location of the r -process. We also briefly mention the post-processing of the r -process abundance distribution through neutron emissions by the nuclei highly excited in ν_e captures and neutral-current neutrino interactions. We summarize our discussions and give conclusions in Sec. 6.

2. POSSIBLE r -PROCESS IN THE NEUTRINO-DRIVEN WIND

For the lack of a good astrophysical model, many studies characterize the conditions for the r -process with the neutron number density and the temperature at the freeze-out of the r -process (see e.g., [3]). Sometimes a neutron exposure time is also introduced. The r -process abundance distributions produced under a set of different conditions are then superposed with appropriate weights to fit the observed solar r -process abundance distribution. In the recent model of the r -process in the neutrino-driven wind, the important physical parameters are the electron fraction, Y_e , the entropy per baryon, S , the dynamic time scale, τ_{dyn} , and the mass loss rate, \dot{M} , in the wind. All these parameters are determined mostly by ν_e and $\bar{\nu}_e$ absorptions on the free nucleons in the wind at temperatures much higher than what is relevant for the r -process. Once these parameters are fixed, the adiabatic expansion of a particular mass element in the wind specifies its temperature, T , and density, ρ , as it moves away from the neutron star. It is convenient to think of the radius of this mass element, r , as a time evolution parameter. We can relate the time, t , to r through $dt = dr/v$, with v the velocity of the mass element. For example, in a radiation-dominated wind with $\tau_{\text{dyn}} \sim r/v \sim \text{constant}$, from $\dot{M} = 4\pi r^2 \rho v$ and $S \propto T^3/\rho$, we have $T \propto r^{-1}$, $\rho \propto r^{-3}$, and $r \propto \exp(t/\tau_{\text{dyn}})$ to describe the adiabatic expansion of the mass element. The nucleosynthesis in the mass element can then be characterized by Y_e , S , and τ_{dyn} , with the neutron excess given by $1 - 2Y_e$, and the time evolution of T and ρ specified by S and τ_{dyn} . In other words, these three parameters determine the neutron number density and the temperature at the freeze-out of the r -process and the neutron exposure time in the neutrino-driven wind. The parameters Y_e , S , τ_{dyn} , and \dot{M} in the wind depend on the supernova neutrino flux. The supernova neutrino characteristics evolve on time scales $\sim 1 \text{ s} \gg \tau_{\text{dyn}}$, which naturally leads to a superposition of the r -process abundance distributions produced under various conditions within a single astrophysical event. The mass loss rate determines the relative r -process contribution made with the corresponding Y_e , S , and τ_{dyn} . When integrated over the neutron star Kelvin-Helmholtz cooling time scale, it also gives the total amount of the r -process material ejected in each supernova. Therefore, in principle, this model could reproduce the observed solar r -process abundance distribution and account for the galactic r -process yields without fine-tuning any arbitrary parameter [4].

A simplistic picture for the physical processes leading to the r -process in the neutrino-driven wind is as follows. At $T_9 \gtrsim 10$ (T_9 stands for the temperature in 10^9 K), the wind material is essentially composed of free nucleons. The absorptions of ν_e and $\bar{\nu}_e$ on free neutrons and protons, respectively, are the main heating mechanisms to drive the expansion of the material. In the meantime, these absorption reactions also govern the evolution of the electron fraction at these temperatures. At $10 \gtrsim T_9 \gtrsim 5$, nuclear statistical

equilibrium approximately holds, and the wind material mostly consists of free nucleons and α -particles. All the physical parameters in the wind have been set by the time the temperature reaches $T_9 \sim 5$. In general, the mass loss rate is set first, followed by the entropy and the dynamic time scale. The electron fraction is set last [2]. For $Y_e < 0.5$ and $S > 100$ per baryon, an α -process takes place at $5 \gtrsim T_9 \gtrsim 3$, resulting in seed nuclei of mass number $A_s \sim 100$ [1]. At $3 \gtrsim T_9 \gtrsim 1$, the r -process occurs under neutron-rich and possibly α -rich conditions. In the following sections, we discuss the role of neutrino-nucleus interactions in the various physical processes described above. As we will see, these discussions complicate the simple picture of the r -process in the neutrino-driven wind. Nevertheless, they also provide a better understanding of the physical conditions for a successful supernova r -process.

3. DETERMINATION OF THE ELECTRON FRACTION

Obviously, the r -process only operates under neutron-rich conditions. In other words, an r -process is possible only if the electron fraction is set at $Y_e < 0.5$. At $T_9 \gtrsim 10$, the following reactions are important for setting the electron fraction in the neutrino-driven wind:

$$\nu_e + n \rightleftharpoons p + e^-, \quad (1)$$

$$\bar{\nu}_e + p \rightleftharpoons n + e^+. \quad (2)$$

To first approximation, the evolution of the electron fraction in the wind is determined by

$$\frac{dY_e}{dt} \equiv v \frac{dY_e}{dr} = \lambda_1 - \lambda_2 Y_e, \quad (3)$$

where $\lambda_1 = \lambda_{\nu_e n} + \lambda_{e^+ n}$, and $\lambda_2 = \lambda_1 + \lambda_{\bar{\nu}_e p} + \lambda_{e^- p}$. We denote the rates for the forward reactions in Eqs. (1) and (2) as $\lambda_{\nu_e n}$ and $\lambda_{\bar{\nu}_e p}$, respectively. The rates for the corresponding reverse reactions are denoted by $\lambda_{e^- p}$ and $\lambda_{e^+ n}$, respectively. It can be shown that as long as the rate λ_2 is larger than the expansion rate of the wind material, the electron fraction is approximately given by $Y_e \approx \lambda_1/\lambda_2$ [2]. If this still holds when the temperature-sensitive rates $\lambda_{e^- p}$ and $\lambda_{e^+ n}$ become negligible compared with the neutrino absorption rates $\lambda_{\bar{\nu}_e p}$ and $\lambda_{\nu_e n}$, the electron fraction depends on the ratio $\lambda_{\bar{\nu}_e p}/\lambda_{\nu_e n}$ alone, and is given by

$$Y_e \approx \left(1 + \frac{\Phi_{\bar{\nu}_e} \langle E_{\bar{\nu}_e}^2 \rangle - 2\Delta \langle E_{\bar{\nu}_e} \rangle + \Delta^2}{\Phi_{\nu_e} \langle E_{\nu_e}^2 \rangle + 2\Delta \langle E_{\nu_e} \rangle + \Delta^2} \right)^{-1}, \quad (4)$$

where for example, Φ_{ν_e} and $\langle E_{\nu_e}^n \rangle$ are the ν_e flux and the n th moment of the normalized ν_e energy spectrum, respectively. The neutron-proton mass difference, $\Delta = 1.293$ MeV, enters Eq. (4) through the dependence of the neutrino absorption cross sections on the phase space of the outgoing leptons [2].

Equation (4) connects the electron fraction in the wind with the characteristics of supernova neutrino emission. The neutron-rich material inside the neutron star gives rise to different opacities for ν_e and $\bar{\nu}_e$ through the forward reactions in Eqs. (1) and (2). As a result, $\bar{\nu}_e$ decouple at higher temperatures inside the neutron star than ν_e , and correspondingly have a harder spectrum. In terms of the average neutrino energy, $\langle E_\nu \rangle$,

and the effective neutrino energy, $\epsilon_\nu \equiv \langle E_\nu^2 \rangle / \langle E_\nu \rangle$, we have $\langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$ and $\epsilon_{\bar{\nu}_e} > \epsilon_{\nu_e}$. The difference between the $\bar{\nu}_e$ and ν_e spectra increases as the neutron star becomes more and more neutron rich with time. The neutrino flux can be written as $\Phi_\nu \propto L_\nu / \langle E_\nu \rangle$, with L_ν the neutrino luminosity. Numerical supernova neutrino transport calculations show that $L_{\bar{\nu}_e} \approx L_{\nu_e}$ for the first 20 s of the neutron star cooling phase [4]. During this time, Eq. (4) can be rewritten as $Y_e \approx (\epsilon_{\bar{\nu}_e} + 2\Delta) / (\epsilon_{\bar{\nu}_e} + \epsilon_{\nu_e})$, with the terms proportional to Δ^2 neglected. Therefore, an r -process can possibly occur only if $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} > 4\Delta \approx 5.2$ MeV. This corresponds to $t \gtrsim 3$ s after the supernova explosion (see Fig. 5 in Ref. [2]). Typically, we have $\epsilon_{\bar{\nu}_e} \approx 22$ MeV and $\epsilon_{\nu_e} \approx 12$ MeV, which give $Y_e \approx 0.43$. Of course, when the r -process actually takes place also depends on other physical parameters in the wind, such as the entropy per baryon.

It is conceivable that the approximate equality of $L_{\bar{\nu}_e}$ and L_{ν_e} breaks down when the deleptonization of the neutron star is nearly complete. This may occur between 20 and 30 s after the supernova explosion. At these very late times, the approximate equality of $\Phi_{\bar{\nu}_e}$ and Φ_{ν_e} is likely to hold instead. According to Eq. (4), the electron fraction in the wind becomes even more sensitive to the difference between the $\bar{\nu}_e$ and ν_e spectra. In this case, very low values of Y_e may be obtained. With the same neutrino spectra typical of earlier times, and assuming $\epsilon_\nu \propto \langle E_\nu \rangle$, we have $Y_e \approx 0.29$. We note that the larger difference between the $\bar{\nu}_e$ and ν_e spectra at later times may give an even lower Y_e . This could prove extremely helpful when the desirable entropy per baryon in the wind is hard to achieve, and/or the effects considered in the next section become important.

4. INFLUENCE OF THE α -PARTICLES

It was shown in Ref. [2] that the neutrino absorption reactions in Eqs. (1) and (2) are also responsible for setting the entropy per baryon, the dynamic time scale, and the mass loss rate in the wind. Typical entropies are $S \sim 100$ per baryon, and the wind is radiation-dominated [2]. For entropies of $S \gtrsim 100$ per baryon, photo-dissociations of nuclei heavier than α -particles are still strong at $T_9 \lesssim 10$ due to the significant presence of energetic photons on the tail of the Bose-Einstein distribution. Therefore, α -particles become an important part of the nuclear composition in the wind at $T_9 < 10$.

In the presence of α -particles, Eq. (3) for the evolution of Y_e in the wind is modified to be

$$\frac{dY_e}{dt} = \lambda'_1 - \lambda_2 Y_e, \quad (5)$$

where $\lambda'_1 = (1 - X_\alpha)\lambda_1 + (X_\alpha/2)\lambda_2$, with X_α the mass fraction of α -particles. In deriving Eq. (5), we have assumed that free nucleons and α -particles dominate the nuclear composition of the wind. This approximation is good for $10 \gtrsim T_9 \gtrsim 5$. For typical dynamic time scales in the wind, the rate λ_2 is still significant at $T_9 \sim 5$. So the final value of Y_e is affected by the presence of α -particles. The effect of the α -particles can be seen from the instantaneous equilibrium value of $Y_e = (\lambda_1/\lambda_2)(1 - X_\alpha) + X_\alpha/2$ corresponding to Eq. (5). For $\lambda_1/\lambda_2 < 1/2$, α -particles tend to increase Y_e above the value given by Eq. (4). This undesirable effect on Y_e for the r -process in the wind was first pointed out in Ref. [5]. To avoid this effect, one must have a short dynamic time scale, for which Y_e freezes out at $T_9 \gtrsim 10$ when $X_\alpha \approx 0$. In the absence of readily available mechanisms to achieve

such dynamic time scales, we may have to consider a low ratio λ_1/λ_2 to counteract the increase in Y_e from the effect of α -particles. Without invoking exotic neutrino physics such as antineutrino oscillations [6], we may have to consider the scenario of getting low Y_e at very late times suggested in the previous section. The large abundance of α -particles presents yet another serious effect on the potential r -process nucleosynthesis in the wind, which we discuss next.

In the successful r -process calculation of Ref. [4], α -rich conditions were obtained with entropies of $S > 400$ per baryon in the wind. We can understand its success by estimating the neutron-to-seed ratio prior to the r -process obtained in the calculation. The seed nuclei come from the so-called α -process, which occurs at $5 \gtrsim T_9 \gtrsim 3$. To make heavy seed nuclei from α -particles, the nuclear flow has to pass the bottle-neck of the three-body reactions $\alpha + \alpha + \alpha \rightarrow {}^{12}\text{C}$ and $\alpha + \alpha + n \rightarrow {}^9\text{Be}$. Once the bottle-neck is passed, further α -capture reactions proceed efficiently. By the time the Coulomb barrier stops the charged-particle reactions at $T_9 \sim 3$, the nuclear flow has reached seed nuclei of mass number $A_s \sim 100$. Because of the inefficiency of the three-body reactions, the final α -particle mass fraction, $X_{\alpha,f}$, is still high at the end of the α -process. From charge conservation, we have $Y_e \approx X_{\alpha,f}/2 + (Z_s/A_s)X_s$, with $Z_s \sim 35$ the charge of the seed nuclei. At $T_9 \sim 5$, the wind material mostly consists of free neutrons and α -particles, with the neutron mass fraction $X_n \approx 1 - 2Y_e$. At $5 \gtrsim T_9 \gtrsim 3$, neutrons are also captured to make heavy seed nuclei, and X_n decreases somewhat during the α -process. The neutron-to-seed ratio prior to the r -process is approximately given by

$$\frac{n}{s} \approx \frac{X_n}{X_s/A_s} \lesssim \frac{1 - 2Y_e}{Y_e - (X_{\alpha,f}/2)} Z_s. \quad (6)$$

As we can see, a high α -particle mass fraction at the end of the α -process means a large neutron-to-seed ratio, which is required to produce the r -process abundance peaks at mass numbers $A \sim 130$ and 195 .

However, in the presence of significant neutrino flux, the following neutral-current neutrino spallation reaction can occur:

$$\nu + \alpha \rightarrow t + p + \nu'. \quad (7)$$

Because $\nu_{\mu(\tau)}$ and $\bar{\nu}_{\mu(\tau)}$ do not have the charged-current absorption reactions similar to those of ν_e and $\bar{\nu}_e$ in Eqs. (1) and (2), they decouple at the highest temperatures inside the neutron star and have the hardest spectra. They are mainly responsible for the spallation reactions in Eq. (7). Once a tritium nucleus is produced, the subsequent α -capture reactions $t + \alpha \rightarrow {}^7\text{Li}$ and ${}^7\text{Li} + \alpha \rightarrow {}^{11}\text{B}$ can bypass the bottle-neck of the three-body reactions and therefore, expedite the processing of α -particles into heavy seed nuclei. It was found in Ref. [7] that up to 30 α -particles can disappear as a result of a single spallation reaction. If a significant fraction of the α -particles experience neutrino spallations during the α -process, the reduction of $X_{\alpha,f}$ and the simultaneous excessive production of seed nuclei will decrease the neutron-to-seed ratio. In fact, for the conditions employed in the r -process calculation of Ref. [4], it was found that the neutron-to-seed ratio becomes insufficient for effective production of the abundance peak at $A \sim 195$ after neutrino spallations on the α -particles are included [7].

To avoid significant neutrino spallations on α -particles, we need a short dynamic time scale to reduce the duration of the α -process. Otherwise, we have to require a low Y_e , which compensates for a low $X_{\alpha,f}$, to restore the r -process abundance peak at $A \sim 195$ in the calculation of Ref. [4]. On another note, the high entropies of $S > 400$ per baryon in Ref. [4] still evades a simple physical explanation. Typical entropies in the wind are found to be $S \sim 100$ per baryon [2]. For such relatively low entropies, $X_{\alpha,f}$ is already low even without considering the neutrino spallations, unless the dynamic time scale in the wind is extremely short, $\tau_{\text{dyn}} \ll 0.1$ s [8]. Therefore, a short dynamic time scale or a low Y_e in the wind is helpful to the r -process in both the high and the low entropy scenarios.

5. EFFECTS OF ν_e CAPTURES ON NUCLEI

The influence of the neutrino flux does not stop at the end of the α -process. In fact, the effects of supernova neutrinos can be important during and even after the r -process. In the standard picture (see e.g., [3]), the progenitor nuclei on the r -process path are in $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium during the r -process. The nuclear flow proceeds from one isotopic chain with charge Z to the next with charge $Z + 1$ via nuclear β -decays. However, in the presence of significant neutrino flux, the following reaction can compete with nuclear β -decays:

$$\nu_e + A(Z, N) \rightarrow A(Z + 1, N - 1) + e^-, \quad (8)$$

where $A(Z, N)$ stands for a nucleus with Z protons, N neutrons, and mass number $A = Z + N$. It was first pointed out in Ref. [9] that ν_e captures on the progenitor nuclei can potentially speed up the r -process. The β -decay rate strongly depends on the parent-daughter ground state mass difference, and can vary by more than one order of magnitude for different progenitor nuclei. The slowest β -decays occur at the so-called waiting-point nuclei with magic neutron numbers $N = 50, 82$, and 126 . In fact, the duration of the r -process in the standard picture is essentially controlled by the β -decays of these nuclei. Therefore, ν_e captures on the waiting-point nuclei are of particular interest. It turns out that for the same ν_e luminosity and spectrum, the ν_e captures rates are roughly the same for all the waiting-point nuclei [5,10]. If the duration of the r -process is determined by the ν_e captures instead of the β -decays, the number of ν_e captures during the r -process must satisfy $\Delta Z > 1$. Assuming that the r -process occurs from $T_9 \sim 3$ to $T_9 \sim 1$ in the neutrino-driven wind, we have

$$\Delta Z \sim \lambda_{\nu_e}(r_{\text{FO}}) \int_{r_{\text{FO}}/3}^{r_{\text{FO}}} \left(\frac{r_{\text{FO}}}{r} \right)^2 \frac{dr}{v} \sim 4\lambda_{\nu_e}(r_{\text{FO}})\tau_{\text{dyn}} > 1, \quad (9)$$

where $\lambda_{\nu_e}(r_{\text{FO}})$ is the typical ν_e capture rate at the freeze-out radius of the r -process, r_{FO} , with $\lambda_{\nu_e} \propto r^{-2}$. In deriving Eq. (9), we have made the approximation that the temperature decreases as r^{-1} in the wind with a constant dynamic scale $\tau_{\text{dyn}} \sim r/v$.

However, previous studies of the r -process also indicate that the nuclear flow is dominantly controlled by the β -decays at the freeze-out of the r -process [3]. Therefore, we also have

$$\lambda_{\nu_e}(r_{\text{FO}}) < \lambda_{\beta}, \quad (10)$$

where $\lambda_\beta \sim 3 \text{ s}^{-1}$ is the typical β -decay rate of the waiting-point nuclei (see Table 4 in Ref. [5]). In fact, Eq. (10) was used to constrain the location of the r -process [5]. For typical ν_e luminosities and spectra, Eq. (10) gives a lower limit on r_{FO} of $\sim 100 \text{ km}$. Combining Eqs. (9) and (10), we find that ν_e captures can speed up the r -process without affecting its freeze-out if

$$\tau_{\text{dyn}} > \frac{1}{4\lambda_\beta}. \quad (11)$$

While the quantitative effects of ν_e captures during the r -process can be assessed only in a detailed numerical calculation, some implications of Eq. (11) are readily available. First of all, Eq. (11) tells us that in a wind with a constant dynamic time scale as assumed in deriving Eq. (9), a good r -process is possible only if $\tau_{\text{dyn}} > 0.1 \text{ s}$, for which there is enough time to complete the r -process with the help from ν_e captures. In this case, a low Y_e may be the last hope for the r -process in the neutrino-driven wind. On the other hand, if $\tau_{\text{dyn}} < 0.1 \text{ s}$ is needed to avoid the undesirable effects of α -particles on Y_e and the neutron-to-seed ratio discussed in Sec. 4, the wind has to slow down considerably between the α -process and the r -process. This may be accomplished by imposing an outer boundary temperature of $T_b \sim 10^9 \text{ K}$ on the wind [2]. From $\dot{M} = 4\pi r^2 \rho v$ and $S \propto T^3/\rho$, the velocity decreases according to $v \propto r^{-2}$ after the temperature in the wind reaches T_b for the first time at radius r_1 . The time available for the r -process is approximately given by

$$\Delta t \sim \int_{r_1}^{r_{\text{FO}}} \frac{dr}{v} \sim \frac{\tau_{\text{dyn}}}{3} \left[\left(\frac{r_{\text{FO}}}{r_1} \right)^3 - 1 \right], \quad (12)$$

where we have assumed $r_1/v_1 \sim \tau_{\text{dyn}}$, with v_1 the velocity at r_1 . Without significant ν_e captures, the standard picture requires $\Delta t \sim 1 \text{ s} > \lambda_\beta^{-1}$ to complete the r -process. For $\tau_{\text{dyn}} < 0.1 \text{ s}$, the freeze-out radius of the r -process has to be large to give $\Delta t \sim 1 \text{ s}$.

Finally, we also mention the effects of the supernova neutrino flux after the r -process freezes out. The post-processing of the r -process nuclei by supernova neutrinos was first suggested in Ref. [11]. Here we briefly discuss a somewhat different kind of post-processing, which takes place before the progenitor nuclei successively β -decay to the r -process nuclei observed in nature. We note that the progenitor nuclei are left in highly-excited states after ν_e captures. Being neutron-rich, these nuclei de-excite by emitting several neutrons [10]. Neutral-current excitations by $\nu_{\mu(\tau)}$ and $\bar{\nu}_{\mu(\tau)}$ can also induce neutron emissions from the progenitor nuclei [10]. With adequate exposure to the neutrino flux, these neutrino-induced neutron emissions may modify the r -process abundance distribution. Detailed discussions of the possible modifications will be presented elsewhere [10].

6. CONCLUSIONS

We have discussed various neutrino-nucleus interactions in connection with the r -process in the neutrino-driven wind. We find that a short dynamic time scale in the wind, which is needed to avoid the undesirable effects of α -particles on Y_e and the neutron-to-seed ratio, has to be accompanied by some mechanism to contain the wind during the

r -process. We also find that a low Y_e , which counteracts the undesirable effects of α -particles, possibly arises when the neutron star is almost fully deleptonized. We conclude that a low Y_e and/or a short dynamic time scale may be required to give a successful r -process in the neutrino-driven wind.

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